On the Design and Measurement of a Novel Non-Orthogonal Multi-Beam Network for Triangular Arrays of Three Radiating Elements

Javier García-Gasco Trujillo, Álvaro Noval Sánchez de Toca, Ignacio Montesinos-Ortego, Manuel Sierra Perez
Radiation Group, Systems and Radiocommunications Department
Technical University of Madrid
Ciudad Universitaria, Madrid, Spain
{jtrujillo, anoval, nacho, m.sierra.perez}@gr.ssr.upm.es

***Abstract*—An innovative dissipative multi-beam network for triangular arrays of three radiating elements is proposed. This novel network provides three orthogonal beams in θ_0 elevation angle and a fourth one in the broadside steering direction. The network is composed of 90° hybrid couplers and fixed phase shifters. In this paper, a relation between network components, radiating element distance and beam steering directions will be shown. Application of the proposed dissipative network to the triangular cells of three radiating elements that integrate the intelligent antenna GEODA will be exhibited. This system works at 1.7 GHz, it has a 60° single radiating element beamwidth and a distance between array elements of 0.57 λ. Both beam patterns, theoretical and simulated, obtained with the network will be depicted. Moreover, the whole system, dissipative network built with GEODA cell array, has been measured in the anechoic chamber of the Radiation Group of Technical University of Madrid, demonstrating expected performance.**

Butler matrix; phased arrays; adaptive arrays; nonlinear network analysis; multi-beam forming networks (key words)

I. Introduction

From the beginning of telemetry, tracking and command (TT&C) systems, mechanical scanning antennas have been employed at ground stations. As it is well-known, this technique is not only sensitive to gravity and mechanical failure but also slow, making simultaneous satellite communications infeasible. The use of electronically scanned antenna arrays overcomes these limitations, allowing much faster multi-beam scans without physical antenna rotation, [1,2]. These types of systems that use information from the link environment to set the beam shape are called intelligent architectures [3].

In order to improve the ground station performance, many studies have been carried out in the field of electronic scanning systems, in which large arrays composed of thousand of radiating elements have been considered. Generally, these array structures are divided into subarrays based on cells of at least three radiating elements [4-6]. This segmentation reduces the total number of active circuits required, such as amplifiers or phase shifters [7], decreasing total cost and improving efficiency. However, this simplification may imply short restriction in the beam steering precision control that must be taken into account [8]. Electronic steering technique is based on the control of the relative phase associated to each antenna that composes the whole array. The relative phase can be modified by using signal processing algorithms, e.g. MUSIC [9] or ESPRIT [10], or placing phase shifter circuits inside the hardware antenna.

Nowadays, software/hardware hybrid architectures are gaining special interest because its versatility. Therefore, the study of structures that provides multiple beams in different spatial range associated to each cell is needed. In this paper, a new multibeam network configuration that provides three orthogonal beams in θ_0 elevation angle and an extra one with broadside steering direction by feeding a triangular array of three radiating elements will be introduced. Section II will present a short introduction to the state of art of classical multi-beam networks [11, 12]. Section III will comment lossless networks analysis, including two original lossless networks designs [13]. Section IV will show general dissipative matrices theory as well as many applications for array antennas of three radiating elements. In Section V final multi-beam network proposed will be simulated, built and measured in a practical case. Finally, Section VI will collect the conclusion drawn during the paper.

II. General MBFM Scheme

One of the most important tasks in a phased array antenna is designing the beam forming network (BFN). A BFN essentially provides the necessary amplitudes and phases to the radiating elements to produce the desired beams. In particular, for a multiple-beam array, an appropriate BFN is vital in order to distribute the signals to the radiating ports properly.

Most common types of BFNs are presented in [7], where Butler matrix, Blass network, Rotman lens and many more are explained. Some of the designs studied in this paper are based on Butler matrix modifications. Butler matrix is employed to produce 2^n orthogonal beams in linear arrays composed of 2^n radiating elements, where n is a positive integer. Changing some configuration details it is possible to break the limits of this useful network, as will be shown later.

BFNs behavior is characterized by its scattering matrix, where each matrix element represents the mutual coupling between each input and output. Considering inputs and outputs adapted and isolated from each other, an MxN network responds to the scattering matrix defined in (1),

$$[S]=\begin{bmatrix} 0 & \cdots & 0 & S_{1,M+1} & \cdots & S_{1,M+N} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & S_{N,M+1} & \cdots & S_{N,M+N} \\ S_{N+1,1} & \cdots & S_{N+1,M} & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ S_{N+M,1} & \cdots & S_{N+M,M} & 0 & \cdots & 0 \end{bmatrix}=\begin{bmatrix} 0 & S_R \\ S_T & 0 \end{bmatrix} \quad (1)$$

where S_T equals S_R^H if the network is reciprocal.

III. Lossless Network For Triangular Arrays

When a network is reciprocal and lossless, the product of the scattering matrix and its transpose conjugate is the identity matrix,

$$[S][S]^H=[I] \quad (2)$$

This implies that vectors related to the columns of each matrix S_T and S_R have to be orthonormal to each. Hence,

- The number of input and outputs must be the same. Otherwise, matrices would be non-square matrices and one of them would have more vectors than matrix range wherewith it would be impossible to obtain orthogonal beams to each.
- Unitary excitations indicate that the output power is equal to the input power.
- Vectors are orthogonal. When an input port is excited, the radiation pattern obtained will be orthogonal to any other one generated by any other input port.

A. Basic Equations

In order to analyze a triangular 'cell', it is assumed patches are located over vertices of an equilateral triangle with d side length. Figure 1 shows a scheme where: $x_1=\frac{d}{2\sqrt{3}}$, $y_1=\frac{d}{2}$; $x_2=\frac{d}{2\sqrt{3}}$, $y_2=-\frac{d}{2}$; $x_3=-\frac{d}{\sqrt{3}}$, $y_3=0$.

Considering the steering direction of the first beam as $\theta=\theta_0$, $\phi=0$, and taking into account that the array factor is given by,

$$AF(\theta,\phi)=\sum_{i=1}^{3}A_i e^{-j\alpha_i}e^{-jk\hat{r}r_i} \quad (3)$$

Contemplating the fact that feeding phases must satisfy the condition of adding the contributions of each array element in the steering direction, then,

$$k_0\hat{r}r_1-\alpha_1=k_0\hat{r}r_2-\alpha_2=k_0\hat{r}r_3-\alpha_3 . \quad (4)$$

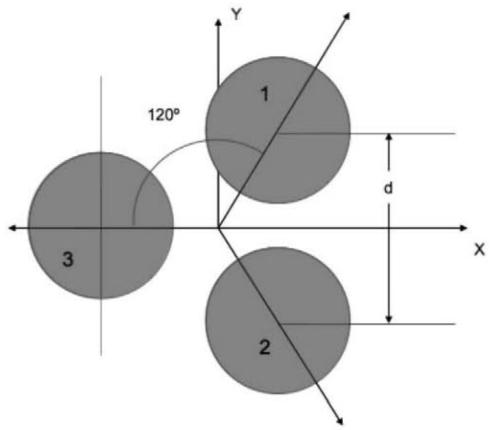


Fig.1: Subarray distribution

Hence, it is shown that,

$$S_{4,1}=S_{5,1}=ae^{j\alpha} \quad (5.1)$$

$$S_{6,1}=be^{j(\alpha-\beta)} \quad (5.2)$$

where ,

$$\beta=\sqrt{3}\frac{\pi d}{\lambda}\sin(\theta_0) . \quad (5.3)$$

Rotating S parameters, (5.1) and (5.2), three different beams are obtained. The other two beams will be orthogonal, keeping a rotational symmetry with the same elevation angle and ±120º related to the azimuth angle.

Imposing the orthogonal condition, (2), ensured through mutually orthogonal excitation vectors at the array port,

$$\sin(\theta_0)=\frac{\lambda}{\sqrt{3}\pi d}\arccos\left(-\frac{a}{2b}\right) \quad (5.4)$$

Main steering directions θ_0, depends on both, distance and feeding signal relation, between elements. Table I shows array factor θ_0 for different distances between elements d, and different amplitude/phase feeding relation a/b, (note: it does not take into account the radiation pattern of the single radiating element).

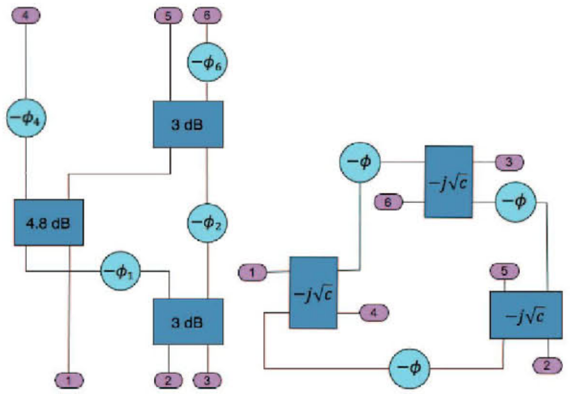
TABLE I. ARRAY FACTOR STEERING DIRECTION

		d/λ			
		0.5	0.6	0.7	0.8
a/b	β	θ_0	θ_0	θ_0	θ_0
0.5	104.5	42.1	34.0	28.6	24.8
0.7	110.5	45.1	36.2	30.4	26.3
1.0	120.0	50.3	39.9	33.4	28.8
1.3	130.5	56.9	44.3	36.7	31.6
1.5	138.6	62.8	47.8	39.4	33.8

Should be noted that when the feeding amplitude is the same for the three elements then it is needed a 120º feeding phase shifts β.

B. Lossless Network Designs

Once analysis has been performed, the hard task is to find structures that fulfill the desired behavior. Different 3x3 MBFN schemes based on hybrid couplers and fixed phase shifter has been studied, [13]. Figure 2 (a) shows a scheme based on Butler network that provides uniform amplitude *a/b* equals 1 with β equals 120º. Figure 2 (b) depicted a rotation symmetric scheme that offers a perfect symmetrical behavior between inputs and outputs. Intrinsic features of these networks limit the number of beams provided at the number of radiating elements and impose the orthogonally between those beams. This analysis shows the need for a beam in the broadside direction. Therefore, this research leads to consider the possibility of using dissipative networks, which are capable of providing a higher number of beams than the radiating elements compounding the cell.



(a) (b)

Fig. 2: (a) Scheme of a three port modified Butler network. (b) Scheme of a three port symmetric network

IV. Dissipative Network for Triangular Arrays

Because of these networks have losses, there is no need to accomplish beams orthogonal condition, which gives a greater degree of freedom that could be used to control beam steering directions. It is worth noting the orthogonal condition ensures maximum array gain. However, when radiating elements are related to radiofrequency circuits in which amplifiers are found, the relevant parameter is the factor G/T that shows the quality of the antenna. As a result, there is no problem on using dissipative network whenever there is an amplifier stage.

The scattering matrix associated to the dissipative network under study, which has three orthogonal beams in θ_0 (columns 2 to 4) and an additional beam in the broadside direction (column 1), is as follows,

$$[S_T] = \begin{bmatrix} f & be^{-j\beta} & a & a \\ f & a & be^{-j\beta} & a \\ f & a & a & be^{-j\beta} \\ g_1 e^{j\alpha_1} & g_2 e^{j\alpha_2} & g_3 e^{j\alpha_3} & g_4 e^{j\alpha_4} \end{bmatrix}. \quad (6)$$

The steering direction of the three orthogonal beams depends on the feeding factors, (b,c), and on the distance between elements of the array, (d), and it is giving by,

$$\sin(\theta_0) = \frac{\lambda}{\sqrt{3}\pi d}\cos^{-1}\left(\frac{a^2+b^2-1}{2ab}\right). \quad (7)$$

Losses associated with the network are related to the broadside beam power as,

$$g_1 = 1 - 3f^2 \quad (8)$$

$$g_i = f^2 \text{ con } i = 2,3,4 \quad (9)$$

Several dissipative networks for triangular arrays have been studied. The most common difficult, is to avoid the appearance of side lobes and diffraction, as shown in [13], where the truncated Butler network for three radiating elements shown in Fig. 3 was presented and analyzed.

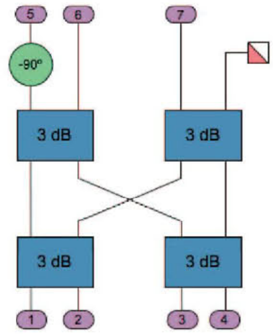


Fig. 3: Scheme of a 4x3 modify Butler matrix

Finally, a network as shown in Fig. 4, is proposed. This network is composed of four 3 dB 90º couplers, four fixed phase shifters and an additional $20\log\left(\sqrt{c}\right)$ dB 90º coupler. Its scattering matrix S_T is given by,

$$[S_T] = \frac{1}{2}\begin{bmatrix} e^{-j\alpha}-\sqrt{1-c} & -j\left(e^{-j\alpha}+\sqrt{1-c}\right) & -\sqrt{c} & j\sqrt{c} \\ -j\left(e^{-j\alpha}+\sqrt{1-c}\right) & -\left(e^{-j\alpha}-\sqrt{1-c}\right) & -j\sqrt{c} & -\sqrt{c} \\ -\sqrt{c}e^{-j\phi_3} & -j\sqrt{c}e^{-j\phi_3} & \left(-\left(e^{-j\alpha}-\sqrt{1-c}\right)\right)e^{-j\phi_3} & \left(-j\left(e^{-j\alpha}+\sqrt{1-c}\right)\right)e^{-j\phi_3} \\ j\sqrt{c}e^{-j\phi_4} & -\sqrt{c}e^{-j\phi_4} & \left(-j\left(e^{-j\alpha}+\sqrt{1-c}\right)\right)e^{-j\phi_4} & \left(e^{-j\alpha}-\sqrt{1-c}\right)e^{-j\phi_4} \end{bmatrix} \quad (10)$$

The analysis of the scattering parameters of the network shows the relation between components. This analysis seeks to match the scattering matrix associated to the dissipative network proposed, (10), to the desired pattern scattering matrix, (6). It shows the behavior of the network is governed by the value of the central coupler, which determines the phase shifters needed. The relation between the steering direction angle θ_0 and the phase shift between elements β is given by,

$$\beta = \sqrt{3}\pi \frac{d}{\lambda} \sin(\theta_0) \tag{11}$$

The steering direction of the orthogonal beams as well as losses associated with each of the beams depends on the coupler c as,

$$\sin(\theta_0) = \tan^{-1}\left(\frac{-2\sqrt{1-c}}{-\sqrt{c}}\right)\frac{1}{\sqrt{3}\pi}\frac{\lambda}{d} \tag{12}$$

$$L_{\theta_0} = -10\log\left(1-\frac{c}{4}\right) \tag{13}$$

$$L_{\theta_0} = -10\log\left(\frac{3}{4}c\right) \tag{14}$$

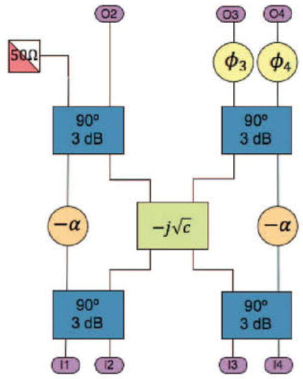


Fig. 4: 4x3 dissipative network

Table II shows beam steering directions θ_0 and distributed signal amplitudes and phases depending on the parameters c, α and d. Losses introduced by the network are also calculated, both θ_0 beams steering direction, L_{θ_0}, and broadside beams, L_{0°, Table III.

TABLE II. STEERING DIRECTION DEPENDING ON PARAMETERS C AND DISTANCES BETWEEN RADIATING ELEMENTS D

					θ_0 *para* d/λ [º]			
c	**a**	**b**	**β [º]**	**α**	**0.5**	**0.6**	**0.7**	**0.8**
0.00	0.000	1.000	-90.0	0.0	-35.3	-28.8	-24.4	-21.2
0.10	0.025	0.925	-99.5	18.4	-39.6	-32.1	-27.1	-23.5
0.20	0.050	0.850	-104.0	26.6	-41.9	-33.8	-28.5	-24.7
0.30	0.075	0.775	-108.1	33.2	-43.9	-35.3	-29.7	-25.7
0.40	0.100	0.700	-112.2	39.2	-46.0	-36.9	-31.0	-26.7
0.50	0.125	0.625	-116.6	45.0	-48.4	-38.6	-32.3	-27.9
0.60	0.150	0.550	-121.4	50.8	-51.2	-40.5	-33.8	-29.2
0.70	0.175	0.475	-127	56.8	-54.8	-42.9	-35.7	-30.7
0.80	0.200	0.400	-135.0	63.4	-60.0	-46.2	-38.2	-32.8
0.90	0.225	0.325	-146.3	71.6	-69.8	-51.5	-42.1	-36.0
1.00	0.250	0.250	-180.0	90.0	--	-74.2	-55.6	-46.2

TABLE III. LOSSES NETWORK RELATED TO *C* COUPLING

c	**L_θ [dB]**	**L_0 [dB]**
0.00	0.00	∞
0.10	0.11	11.3
0.20	0.22	8.24
0.30	0.34	6.48
0.40	0.46	5.23
0.50	0.58	4.26
0.60	0.71	3.47
0.70	0.84	2.80
0.80	0.97	2.22
0.90	1.11	1.71
1.00	1.25	1.25

V. IMPLEMENTATION OF THE PROPOSED 4X3 NETWORK

Microstrip application of the proposed dissipative network to the triangular cells of three radiating elements that integer the intelligent antenna GEODA, which is composed of 2.700 radiating elements working at 1.7 GHz with a 60º single radiating element beamwidth and a distance between array elements d of 0.57 λ [6, 14, 15], is exhibited in this section.

Looking for a simple and small size implementation, a practical network could be given by using c equals 0.5. In this case, all 90º hybrid couplers utilized are 3 dB and they all can be implemented easily by using commercial 3dB 90º hybrid couplers, such as Mini Circuits QCN-25. Phase shifters are obtained by additional fixed length lines when is required. The scattering matrix associated to this network, obtained by replacing matrix (10), will be,

$$|S_T| = \begin{bmatrix} 0.353 & 0.791 & 0 & 0.353 \\ 0.791 & 0.353 & 0.353 & 0.353 \\ 0.353 & 0.353 & 0.353 & 0.791 \\ 0.353 & 0.353 & 0.791 & 0.353 \end{bmatrix} \arg[S_T] = \begin{bmatrix} -90^\circ & -116.6^\circ & -180^\circ & -270^\circ \\ -116.6^\circ & 90^\circ & -90^\circ & -180^\circ \\ 0^\circ & 90^\circ & -90^\circ & 63^\circ \\ 0^\circ & 90^\circ & -206.6^\circ & -180^\circ \end{bmatrix} \tag{15}$$

The radiating element used consists of two stacked circular patches. As it is shown in [13], the bandwidth of its radiation pattern is on the order of 60º.

With the aim of checking a correct performance, the ideal network has been simulated by utilizing Advanced Design System (ADS) 2009, Fig. 5. The scattering matrix shows a perfect behavior. Once the ideal architecture shows a good performance, the real network is simulated by using measured s parameters of both, phase shifters and QCN-25 90º 3dB hybrid coupler, showing agreement with expectations.

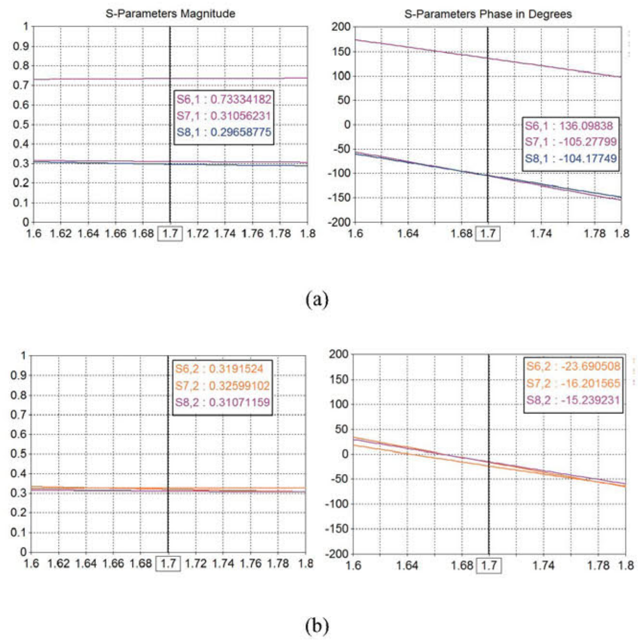


Fig. 5: Simulated scattering parameters of the real dissipative 4x3 network. (a) θ_0 tilt beam, and (b) broadside beam.

The network has been implemented in microstrip RO4350B, Fig. 6. Fixed phase shifters and 3 dB 90º hybrid couplers QCN-25 have been evaluated independently in order to assure a good performance. The use of commercial couplers is important when total size dimensions must be minimized. The network has ±0.3 dB module error and ±5º phase error, which is acceptable, as it is depicted in Fig. 7 where a comparison between radiation patterns simulated with theoretical and measured *s* parameters shows low beam deviations.

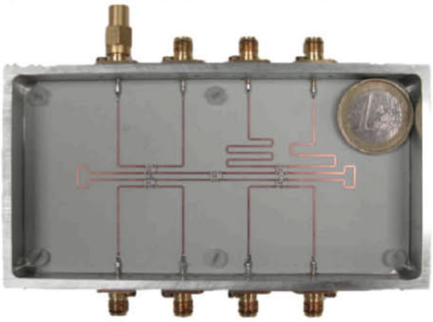


Fig. 6: Microstrip non-orthogonal network

TABLE IV. SCATTERING MATRIX AND LOSSES OF THE 4X3 NETWORK

	O2	O3	O4	β	Losses
I1	$0.700e^{j0.915\pi}$	$0.305e^{-j0.446\pi}$	$0.302e^{-j0.412\pi}$	118.1º±3º	32%
I2	$0.327e^{j0.032\pi}$	$0.312e^{j0.049\pi}$	$0.300e^{j0.068\pi}$	0º±3º	70%
I3	$0.312e^{-j0.951\pi}$	$0.327e^{-j0.969\pi}$	$0.683e^{j0.417\pi}$	112.1º±2º	33%
I4	$0.312e^{j0.537\pi}$	$0.691e^{-j0.108\pi}$	$0.324e^{j0.572\pi}$	119.1º±3º	32%

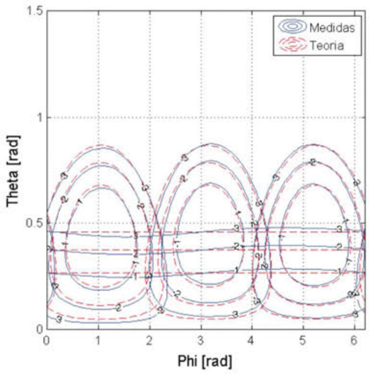
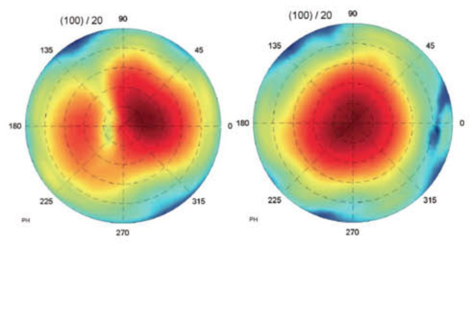


Fig. 7: Simulation of the radiation pattern of the whole system, cell antenna and dissipative network, considering theoretical (red) and measured (blue) *s* parameters

Moreover, the whole system, dissipative network built with GEODA cell array, has been measured in the anechoic chamber of the Radiation Group of Technical University of Madrid, demonstrating expected performance (Fig. 8).



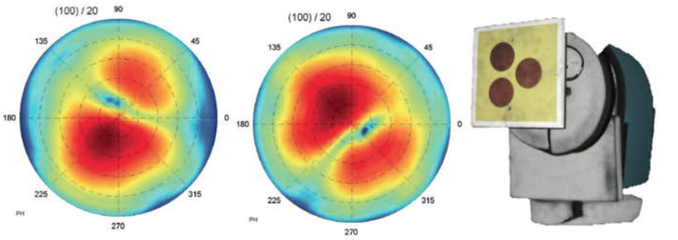


Fig. 8: Measured radiation patterns of the beam forming network and cell subarray GEODA.

VI. CONCLUSIONS

MBFN for triangular subarrays of three radiating elements has been studied. Intrinsic features of lossless network limit the number of beams generated. A novel non-orthogonal network providing three ortogonal θ_0 beams and an extra broadside one has being proposed. Practical implementation of the network integrated to GEODA triangular subarray has been built and measured obtaining expected results.

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